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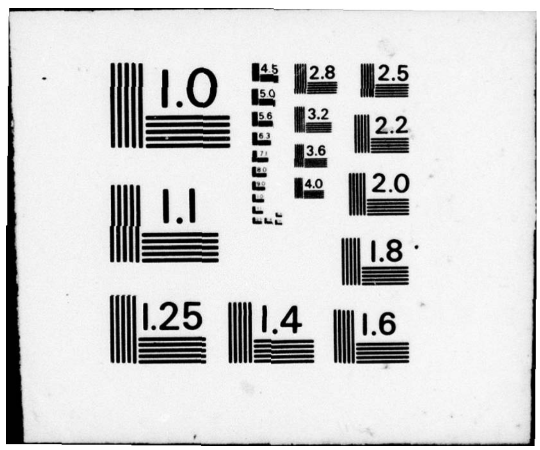
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FINAL REPORT TO THE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

on

SOLID PROPELLANT IGNITION AND UNSTEADY COMBUSTION PROCESSES

AFOSR Grant AF-74-2602
From 1 October 1973 to 30 September 1976

November 1976

Submitted by

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PREFACE

This is the final report issued under Grant AF-74-2602 from the Energetics Division of the Air Force Office of Scientific Research. The period of performance was 1 October 1973 to 30 September 1976. The technical monitor for the initial year of the program was Capt. L. R. Lawrence, USAF. The technical monitor for the remainder of the program was Maj. T. C. Meier, USAF. This document was not archived by NTIS since the details of the research have been or soon will be reported in other archive publications. Several elements of the research which were initiated during the Grant are being continued under a new Grant, AF76-3104.

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1.0 INTRODUCTION

The research program summarized in this final report is part of a continuing study of the physical, chemical, and aerodynamic processes which control and affect the nonsteady burning of solid propellants in rocket motor chambers. The broad objective of the program was the study of combustion dynamics of high performance rocket motor systems together with the underlying physicochemical and aerodynamic processes. This work is intended to provide the development engineer with advanced techniques and guidelines on the capabilities and limitations of experimental and analytical methods for analyzing transient responses in high performance rocket motors. These techniques are taking full advantage of the recently developed experimental data and analytical formulations. Specific elements in the program were continually up-dated by maintaining close contact with the personnel of the Air Force Rocket Propulsion Laboratory.

In addition to the practical motivation for the research, there is an equally powerful scientific motivation. The phenomena that occur in many nonsteady flame and reacting flow field situations have not been adequately explained in terms of physical models and theories. In this sense, the problems of nonsteady flames in rocket chambers represents a scientific challenge. Solutions to these problems have important implications even for the supposedly solved cases of steady state flames. The exploration of nonsteady phenomena is leading to a much more advanced understanding of the physicochemical and fluid mechanical basis of flames.

This final report treats the accomplishments under the grant in two categories. In the first category is work that has progressed to the point of publication. The publications are summarized in Section 2. In the second category is the work that is being continued under a new AFOSR grant, i.e., the evaluation of motor response functions summarized in Section 3 and the aluminum burning research summarized in Section 4.

2.0 ACCOMPLISHMENTS UNDER GRANT

2.1 Publications

During the reporting period, the results of our research were the subjects of technical papers. Since the technical papers are distributed according to the CPIA mailing list as they become available, this report merely contains abstracts (in Section 2.2) of the publications.

The publications summarized in this section are the papers which have been (or will be) archived by the appropriate libraries and agencies. Some types of publications (i.e., preprints of papers later published in journals, progress reports which were superseded by final reports, administrative summary reports which merely summarize other publications listed, and informal presentation summaries) have not been included if the results reported in them are also contained in a more comprehensive archive publication. It should be noted that the interplay among the publications is great since there has been a commonality of propellants, fuels, rocket motors, data reduction techniques, etc., throughout our investigations.

2.2 Abstracts of Publications

2.2.1 Abstract

"INFLUENCE OF THERMAL RADIATION ON SOLID PROPELLANT BURNING RATE."

L. H. Caveny, T. J. Ohlemiller and M. Summerfield

AIAA Journal, Vol. 13, No. 2, February 1975, pp. 202-205.

Radiation assisted burning rate data $[r(q_{rad})]$ and temperature sensitivity of burning rate data $[r(p,T)$ and $\sigma_p = \partial r/\partial T_0)_p]$ were obtained for a well characterized double base propellant (nitrocellulose and metriol trinitrate). For example, at 14.6 atm, 70 cal/sec-cm^2 of xenon arc radiation increased the burning from 0.2 to 0.6 cm/sec. Analysis of the heat feedback from the flame revealed that once $r(T_0)$ data are available, $r(q_{rad})$ data does not permit additional properties of the combustion zone to be deduced. However, a simple analytical relationship between $r(q_{rad})$ and σ_p was developed that approximates the measured results. Propellant burning rate responsiveness to external thermal radiation increases with higher σ_p and lower burning rate.

Based on work performed under Grant AF74-2602 sponsored by the Energetics Division, Air Force Office of Scientific Research.

2.2.2 Abstract

"ACOUSTIC EMISSIONS FROM BURNING PROPELLANT STRANDS."

A. J. Saber, M. D. Johnston, L. H. Caveny, M. Summerfield and J. L. Koury

Proceedings of 11th JANNAF Combustion Conference, 1974, CPIA Publication No. 261, Vol. I, pp. 409-427.

Burning solid propellants produce ultra-high frequency acoustic emissions (UHFAE) which can be detected by a piezoelectric microphone mounted on the outside wall of a strand burner. Previous investigations of solid propellant UHFAE examined the gross aspects of the emissions, i.e., stop/start of the emissions for timing burning intervals and relative RMS signal levels; the objectives of this study include: (1) developing techniques to establish the spectral distribution (i.e., an acoustic emission spectrometer), (2) relating the spectra to particulars of the combustion process, (3) determining whether specific propellants are identifiable from their acoustic signatures, and (4) establishing a basis for recognizing spurious behavior from UHFAE signatures. Most of the effort is directed at the frequencies between 100,000 and 300,000 Hz generated during the combustion of aluminized (20%) and non-aluminized ammonium perchlorate composite propellants (granulation from 0.5 to 400μ) burned under water at constant pressure (30 to 140 atm). Experimental parameters include burning medium, reproducibility, test interval, pressure, strand size, oxidizer size and particle distribution. Systematic tests produced consistent trends of acoustic power versus frequency; although the spectra obtained do not permit specific combustion characteristics to be isolated. Exploration of the spectral structure is continuing.

Based on work performed under Grant AF-74-2602 sponsored by the Directorate of Aerospace Sciences, Air Force Office of Scientific Research and Army Contract DAAA21-72-C-0332 sponsored by the U.S. Army Product Assurance Laboratory of Picatinny Arsenal.

2.2.3 Abstract

"EXPERIMENTAL STUDY OF IGNITION AND SUBSEQUENT FLAME SPREAD OF A SOLID FUEL IN A HOT OXIDIZING GAS STREAM."

T. Kashiwagi, G. G. Kotia and M. Summerfield

Combustion and Flame, Vol. 24, 1975, pp. 357-364.

Characteristics of ignition and subsequent flame spread of solid fuels (PBAA, PIB and paraffin waxes), in a hot oxidizing gas stream were studied experimentally by using a shock tunnel with a flat-plate fuel specimen placed parallel to the flow. Effects of freestream oxygen content (20% - 100%), freestream temperature (1270 - 2100 K), freestream velocity (77-275 m/sec) and diluent inert gases (N_2, Ar) on ignition and flame spread behavior were studied. It was observed that, if the external heating rate is high or if the sample tends to pyrolyze at low temperatures, the heat feedback from the exothermic gas phase reaction is not important and the effects of freestream oxygen content are small for both ignition and flame spread. However, if the external heating rate is small or the sample tends to pyrolyze only at high temperatures, the heat feedback from the exothermic gas phase reaction is important and effects of freestream oxygen content are significant for ignition and flame spread.

Based on work performed under Grant AF74-2602 sponsored by the Energetics Division, Air Force Office of Scientific Research.

2.2.4 Abstract

"EROSIVE BURNING OF NONMETALLIZED COMPOSITE PROPELLANTS - DATA ACQUISITION AND ANALYSIS"

Benjamin B. Stokes, Robert O. Hessler, and Leonard H. Caveny

To appear in Proceedings of 13th JANNAF Combustion Conference, September 1976.

A 50 cm long slab motor with two closely spaced propellant surfaces (e.g., 0.7 cm apart) was used to obtain erosive burning data. The motor was extinguished by liquid quench during the early part of motor operation. Static pressure was measured at 5 axial stations and distance burned was measured directly from the extinguished propellant surfaces. Test results for three nonmetallized AP composite propellants are presented. The data were correlated by using the Lenoir-Robillard equation to deduce the burning rates which produced the best agreement between measured and calculated pressures.

Based on work performed under sponsorship of the Air Force Office of Scientific Research as part of Grant AF-74-2602 and Thiokol Corp./Huntsville Division.

2.2.5 Abstract

"SOLID PROPELLANT ROCKET MOTOR RESPONSE FUNCTIONS EVALUATED BY MEANS OF FORCED LONGITUDINAL WAVES"

Michael M. Micci, Leonard H. Caveny and Martin Summerfield

Paper offered to the AIAA 13th Propulsion Conference to be held in Orlando, Florida on July 11-13, 1977

Controlled nonsteady flow and burning conditions were produced in laboratory-scale solid rocket motors by developing a device that modulated the throat area of the primary nozzle. Modulation frequencies up to 2400 Hz were obtained. The modulated throat rocket motor was used to acquire data using AP composite propellant grains. Cold flow tests were used to study the acoustic modes and nozzle discharge characteristics. Computerized techniques were developed for conducting spectral analyses of head-end and nozzle-end pressure data. The equations describing the nonsteady one-dimensional gas dynamics and propellant combustion were solved using a comprehensive numerical solution. The solution takes into account the couplings among oscillating nozzle flow, nonsteady chamber flow, and erosive burning. Since pressure and velocity oscillations can be made to occur and decay in high loading density rocket motors with realistic grain configurations, the experiment produces propellant/chamber response functions that are relatively easy to interpret.

Based on work performed under sponsorship of the Energetics Division, Air Force Office of Scientific Research, under Grant AF74-2602.

3.0 SOLID PROPELLANT ROCKET MOTOR RESPONSE FUNCTIONS EVALUATED BY MEANS OF FORCED LONGITUDINAL WAVES

3.1 Approach

A methodology centered around the modulated throat rocket motor (MTRM) was developed to investigate and categorize the dynamic responses of high performance rocket motors in which the avoidance of longitudinal mode combustion instability is a consideration. The modulated throat rocket motor establishes (under controlled conditions) periodic longitudinal pressure and velocity oscillations in rocket chambers having small port-to-throat area ratios. The oscillations are set up by alternately restricting and opening a conventional sonic-nozzle throat by means of a slotted, rotating wheel. The rocket motors used in the experiments have high loading densities and are not specially devised apparatuses for testing propellants isolated from the rocket motor chamber environment. As such,

(a) Heat losses are minimized.

(b) The important couplings between the propellant surface, close-in flame zone, and chamber reactions occur naturally.

(c) Velocity and pressure coupling effects and their interactions occur naturally.

Since tests are conducted over the entire duty cycle of motor operation, a single test surveys a full range of L^*'s, internal Mach numbers, and propellant cavity geometries.

The objectives for developing and analyzing the modulated throat rocket motor in which longitudinal waves are important include:

(1) to obtain pressure and velocity coupling response functions under conditions that are close to rocket motor conditions.

(2) to develop a mathematical model that uses experimentally correlated response functions (as opposed to theoretical models) to predict and analyze motor performance.

(3) to develop a means of directly ranking the susceptibility of candidate propellants (specifically with small changes in formulation) to the several types of interactions that lead to instabilities.

Other investigators are using externally excited rocket motors to study nonsteady chamber processes. Brown and coworkers[1,2] at the Chemical Systems Division of United Technologies, used a dual-vented rocket motor (one vent is modulated) in which they obtained propellant response data for bulk mode oscillations that are in good agreement with T-burner results. In addition, they conducted a test series to evaluate velocity coupling effects by increasing the port velocity by a factor of 2.8 and concluded (for their particular case) that velocity coupling effects were not produced. However, their summary report[2] did not specify what type of longitudinal waves were set up, the port to throat area ratio, and the conventional erosive burning characteristics of the propellant. Researchers at ONERA[3,4] have tested several types of modulated throat rocket motors which were designed for the purposes of studying pressure and velocity coupled responses. While their reports describe an apparatus which could possibly be used to study velocity coupling effects, their published results are for short chambers in which the bulk mode processes dominate and the velocity coupling effects have been eliminated. Unsteady combustion studies are underway at JPL[5] in which an end-burning grain is subjected to forced pressure oscillations produced by modulating the exhaust vent of a combustor whose exhaust is mixed with N_2. In this manner, the JPL investigators are able to measure pressure coupled responses. The work being carried out at Princeton University goes beyond the pressure coupling studies reported by other laboratories. Our effort is directed at velocity coupled responses and chamber/propellant interactions resulting from the combustion gases flowing in high performance motors in which longitudinal waves can be sustained.

3.2 Apparatus

The major components of the MTRM are: (1) a conventional rocket motor with a sonic throat (in the present case 25 and 50 cm long motors are being used), the modulating wheel assembly (includes electric motor drive, speed control, and nozzle gap adjustments), and special head-end and nozzle-end closures for flush mounted pressure transducer.

Two methods of modulating throat area have been devised and checked at Princeton University. The first version (see Fig. 1a and 1b) uses a horizontal wheel and is similar in principle to the approach described in Ref. 3. This apparatus was useful in setting up the data reduction methods for analyzing the longitudinal waves produced during cold flow and rocket motor firings. However, the various modulation wheel designs (e.g., circular holes, slots and partial tabs) were not capable of producing truly steady state, low-amplitude longitudinal waves. This shortcoming was attributed to difficulties in holding precise tolerances around the circumference and in maintaining dimensional rigidity. The second version (shown in Fig.2) is a completely redesigned version that uses a vertical wheel. This apparatus takes advantage of precision machining and bearing arrangements which eliminate the difficulties encountered with the horizontal wheel. The test results demonstrated that the vertical wheel design overcame the difficulties which the ONERA investigators described.

The modulating wheel assemblies are modules that can be used in conjunction with a variety of rocket motors. Indeed, plans call for using the modulating wheel with a 50 cm long window motor to obtain high-speed photographs of the interactions produced by the unsteady velocity components and to obtain pressure measurements at five axial stations. Special purpose instrumentation and computer programs were developed and implemented to acquire and analyze the low amplitude pressure-versus-time data with sufficient accuracy. The amplified output from high frequency, strain-gauge-type pressure

transducers (Kulite XTME-1-190) are recorded on a calibrated Honeywell 5600C analog tape recorder at 60 ips and a band width of 10 kHz. The analog data are acquired in several forms, e.g., unfiltered, filtered, and differential pressure. Since steady state oscillations are set up, only selected portions of the analog record are digitized for data reduction using a digital computer. The data reduction procedure consists of Fourier analysis of head-end and nozzle-end pressures, (i.e., p_{head} and p_{noz}), cross-correlation of the p_{head} and p_{noz}, and development of forcing functions for use in the analytical model. Some of the elements in the experiment and data analysis procedures are illustrated in Fig. 3.

A cold flow adaptor was designed and fabricated for one of the rocket motors which is used with the modulating wheel. Air is injected at the head end through a porous brass plate. The pressure drop across the plate is maintained sufficiently high so that the flow across the plate is always choked and, thus, the pressure waves set up in the chamber do not affect the mass flow entering the chamber. The cold-flow apparatus was used for the initial check-out of the instrumentation and to investigate the chamber responses. These data will be summarized in a forthcoming technical note for the purpose of showing the type of chamber responses produced by modulating the throat.

3.3 Mathematical Model

The gas flow and propellant burning rates in the MTRM were modeled so that the measured nozzle-end pressure-versus-time $[p_{noz}(t)]$ can be used as a forcing function. The model employs a solution to the partial differential equations for energy, continuity, and momentum of the chamber flow coupled to boundary conditions at the gas-stream/propellant interface. Since flow through the nozzle is not a consideration in the mathematical formulation, knowledge of how throat area varies with time is not needed. The pressure-coupled response is

calculated using a linearized version of the Zeldovich dynamic burning model and the velocity-coupled response is approximated from steady state erosive burning data. In many respects, the transient flow solution is similar to those described in Refs. 6-8.

The model provides a direct means of testing the validity of candidate methods for calculating the pressure-coupled responses, velocity-coupled responses, and the wave forms in the chamber. In particular, when $\left.p_{noz}(t)\right)_{meas}$ is imposed, the difference between $\left.p_{head}(t)\right)_{meas}$ and $\left.p_{noz}(t)\right)_{calc}$ indicates the degree to which the overall model describes the flow and burning rate responses. The model can be used in the correlation mode by adjusting one or more of the coefficients which are least well defined (e.g., the velocity-coupling surface-blowing coefficient).

Conventional rocket motor performance and stability predictions can be made using the same computer program that is used to analyze the MTRM. The primary difference is the manner in which the nozzle-end boundary includes $\left.p_{noz}(t)\right)_{meas}$ as a forcing function, and (2) when a conventional rocket motor is predicted, the nozzle-end boundary is the conventional converging-diverging nozzle boundary. Thus, once the experimental data have been correlated, the computer program provides a direct means of predicting motor performance. Of course, there are limitations on the type of motors which can be analyzed. The present form of the program is intended for high length-to-diameter motors which do not have complex grain configurations.

Figures 4 and 5 are included for the purpose of illustrating the temporal and spatial output provided by the model. These particular results were calculated for the 25 cm motor under the condition that the throat area was sinusoidally varied ±5%. Note that the mean flow effects, higher harmonics, and exciting frequency (which does match exactly the longitudinal frequency) combine to produce rather complex wave patterns. The actual wave patterns do not contain the clearly defined

nodes and antinodes to which references are often made. Indeed, the magnitude of the velocity disturbance along the port is prominent for about 80% of the chamber length. A complete description of the model and series of calculated results will appear in a forthcoming paper (i.e., Publication 5 in Section 2.1).

3.3 Expected Payoff

The expected payoff from the MTRM approach in terms of motor and propellant stability analysis can be summarized as:

(1) The modulated throat rocket motor subjects the propellant/chamber combinations to prescribable unsteady pressure and velocity conditions (under rocket chamber conditions) and, thus, permits direct measurements of overall responses. A wide range of p, Δp, v, Δv, L^*, A_p/A_t and characteristic times are obtainable.

(2) The apparatus has the potential for determining the relative response (under rocket chamber conditions) of propellant/chamber variations experienced in practice, e.g., effects of raw material lots, small changes in formulation, effect of initial temperature, aging, etc.

(3) The capability of analyzing the unsteady responses in operational rocket motors is improved, since the complete solution to the continuity, momentum, and energy equations which is being used to analyze and interpret the MTRM data is being used also to consider unsteady responses in operational rocket motors.

(4) The interpretation and analysis of the modulated throat rocket motor responses are yielding part of the scientific contributions necessary for understanding nonsteady flames and reacting flow fields.

The methods and approaches which are competing with the MTRM approach include: the wealth of T-burner experience, impedance tube methods, pulsed full-scale rocket motors, and nonlinear internal ballistics theoretical models. The MTRM approach has prompted questions which must be resolved. Some of the questions concern: whether velocity and pressure-coupling combustion processes can be separated; whether propellant-to-propellant variation can be distinguished from test-to-test variations.

4.0 ALUMINIZED SOLID PROPELLANTS BURNING IN ROCKET MOTOR FLOW FIELD

4.1 Approach

The emphasis of this portion of the research is on photographing and interpreting the burning of aluminized propellants under the cross-flow conditions that exist in rocket motors. High-speed photographs ($\sim$ 2000 frames/sec) were taken of the aluminum and aluminum oxide agglomerates forming on the surface, the Al/Al_2O_3 agglomerates moving along the surface and entering the flow field, and the Al/Al_2O_3 agglomerates burning (and undergoing further agglomeration) in the flow field. Several laboratories (most notably the work at NWC, e.g., Refs. 9 and 10) have obtained high resolution photographs of aluminized propellants burning as strands in quiescent atmospheres. These photographs revealed a large amount of information about metal burning processes isolated from the shearing forces of high-speed flow. However, to answer the questions that have been raised concerning metal agglomerate particle size and combustion efficiency (e.g., Ref. 11), the results obtained in quiescent atmospheres must be complemented by results obtained under cross-flow conditions. Other investigators[11,12,13] have studied how formulation, pressure, and port geometry affect the size distribution of metal agglomerates under rocket motor conditions, but those investigations were not concerned with visualizing the combustion processes that produced the agglomerates.

4.2 Analysis

As part of this research, the flow fields containing burning metal/metal oxides were analyzed. Figure 6 illustrates the elements which are part of the mathematical model which was developed. The important new element is the accounting of the burning metal entering the flow field and reacting as it passes down the port. The model accounts for the origin (with respect to axial station) of the burning metal at each axial station (see

Fig. 7) and the degree to which it is reacted. Accordingly, an individual axial increment contains fractions of the aluminum generated at each of the upstream increments. Thus, for most situations, the aluminum as it enters the flow field at the head end of a motor will have a relatively low axial velocity and will be fully burned as it flows along the port. Whereas, the aluminum which enters the flow field near the nozzle end will be accelerated at a higher rate and may be only partially reacted when it enters the nozzle. Unreacted aluminum passing through the nozzle is manifested by lower specific impulses and lower characteristic velocities (i.e., c*).

The fluid flow and aluminum burning situation indicated in Figs. 6 and 7 has been modeled. The burning times of the aluminum agglomerates were calculated from the correlation of Frolov[12] and the agglomerate diameter measurements obtained during the study. According to the Frolov correlations, the agglomerate burning time varies approximately inversely with the concentration of the species (a_k as defined on Fig. 8) that are most reactive with aluminum. Figure 8 illustrates how a_k decreases and flame temperature increases as the aluminum is consumed. The results correspond to the NC/MTN/Al propellants used in our experiments. Figures 9 and 10 show the type of calculated results produced by the model and corresponds to the experiments to be described in this section. [In those experiments the total Al concentration is low (about 1%) because the aluminum is concentrated in a narrow region ($\sim$ 3 mm) to facilitate the photography.] A comparison of the results for the 50 and 5 micron agglomerates shows that the burning times of the large agglomerates are a major fraction of the residence time in the motor, whereas, the smaller, 5μ, agglomerates are fully reacted within the motor port. The results have enabled the study of the agglomerate burning times as a function of propellant and motor chamber conditions. Using the above described computational procedure, the agglom-

erate burning time, the window motor photographs, and observed motor performance may be related using empirical correlations.

4.3 Description of Experiment

High-speed movies were taken of aluminized double-base propellants burning in a 50 cm long window motor, which uses two propellant slabs 2.5 cm wide. Photographing the burning of aluminized propellants in a rocket motor flow field presents several problems not encountered during the photography of strands burning in a quiescent atmosphere. Firstly, the transparency of the windows in the motor (adjacent to the burning propellant) must be maintained. This was accomplished by using a coating which ablates slightly and, thereby, removes the deposits which would normally build up on a glass or quartz window. Secondly, even for the 2.5 cm thick flame (viewed in the window motor), the number of emitting Al/Al_2O_3 agglomerates is so great that it becomes impossible to examine an individual particle in the continuum. Furthermore, since the depth of field is approximately 0.5 cm, photographing the 2.5 cm deep agglomerate cloud obscures the detail of the agglomerates within the region of sharp focus. This depth of field and discrimination problem was overcome by photographing the flame above a thin ($\sim$ 1 to 4 mm wide) strip of aluminized propellant that is sandwiched between two layers of non-aluminized propellant (see Figs. 11 and 12). In this manner, it is possible to visualize the combustion processes of individual agglomerates. Because there is very little tendency for the parallel streams (from the aluminized and non-aluminized propellants) to mix, the local environment of the burning aluminum is approximately the same as it would be if the entire propellant charge were aluminized. As far back as two years ago, high-speed photographs were obtained which revealed many of the details. However, only in the last two months of the grant was it possible to refine the techniques to the point where high resolution movies (suitable for presentation at a technical meeting) could be obtained.

Photographs normal-to-the-propellant surface were obtained by positioning a window parellel to the burning surface. In this manner, the aluminum particles emerging on the surface were visualized over a 6 x 9 mm area.

Another option of the photographic setup is axial scanning of the motor by means of the oscillating mirror. The image of the burning propellant is reflected into the lens system of the camera. In this manner, a single agglomerate can be photographed at reasonably high magnification (about 1:1 image on the film) and tracked for several centimeters in the direction of flow.

Several test series have been conducted in which photographs of burning aluminized propellant were obtained. The greatest success was obtained with the following formulation:

Non-Aluminized Propellant:

NC	53.7%
MTN	39.2%
TEGDN	7.0%

Aluminized Propellant:

Same ratio of NC/MTN/TEGDN but with aluminum added.

The following systematic test conditions have been used throughout the experiments:

Pressures	17, 34, and 68 atm
Al particle size	5, 15, and 40 μm

Two types of aluminum powder have been used:

(1) an as-received (commercial grade) powder, and

(2) a specially treated powder prepared by the AF Rocket Propulsion Lab, referred to as AFCAM.

During a single test a range of cross-flow velocities are encountered since the cross-flow velocity decreases as the port cross-sectional area increases. Accordingly, the maximum cross-flow considered was $\sim$ 200 m/sec and the minimum was < 10 m/sec. Also, for purposes of comparison, photographs

were taken of the propellants burning as 6 x 6 mm strands in a quiescent atmosphere. Since the propellants being used are homogeneous compared to the AP composite propellants considered by Crump in Ref. 9, the mechanism of agglomeration differs somewhat from that described in Ref. 9. Rather than the collection of Al/Al_2O_3 in pockets that form on the surface of propellants containing relatively large (e.g., $\sim$ 50 to 200 μm) solid particles, for the homogeneous propellants, Al agglomerates on the burning surface independently of surface irregularities. Two forces combine to lift the layer from the surface: (1) forces normal-to-the-propellant surface, produced by the combustion gases leaving the surface, and (2) forces parallel to the propellant surface, produced by the shearing action of the cross flow.

For some low burning rate conditions, the specially treated aluminum prepared by the AF Rocket Propulsion Lab is known to produce higher overall motor efficiencies. This improvement has been attributed to the AFCAM producing smaller agglomerates and, as a consequence, reducing two-phase flow losses and burning more completely. If this is the case, agglomerate size differences should be apparent in the photographs. The photographs revealed an unexpected result -- the agglomerates were so large (i.e., 300 - 1000μ) that the two-phase flow velocity differences even in the low flow regions are on the order of one-half of the main stream flow (see Fig. 13). During the continuation study, additional particle size information will be obtained from the photographic records. However, as can be seen, the two-phase flow lags for the AFCAM are only slightly less than for the as-received aluminum powder and, as a result, the differences in the agglomeration characteristics of the two propellants are not immediately apparent.

The primary observables in the experiment are: agglomerate dimensions on the propellant surface (prior to entering the flow stream) as a function of time, agglomerate dimensions in the flow stream as a function of time (i.e., time required to

form a sphere), frequency of two agglomerates merging to form a larger agglomerate, agglomerate axial velocity, and extent of "combustion tail" of Al_2O_3 smoke

During the continuation studies, a set of correlation parameters for the observables will be expressed in terms of pressure (p), cross-flow velocity (V), port hydraulic diameter (d_h), and propellant burning rate (r).

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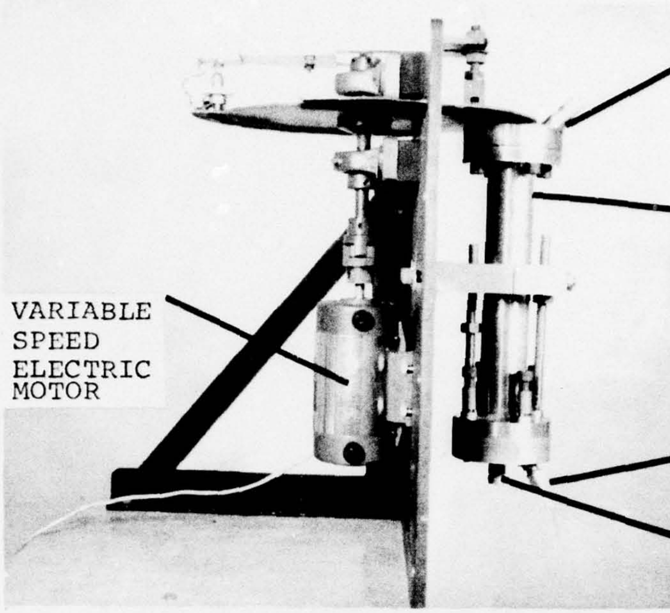


Fig. 1a Modulated throat rocket motor that uses horizontal wheel to periodically interrupt discharge through nozzle.

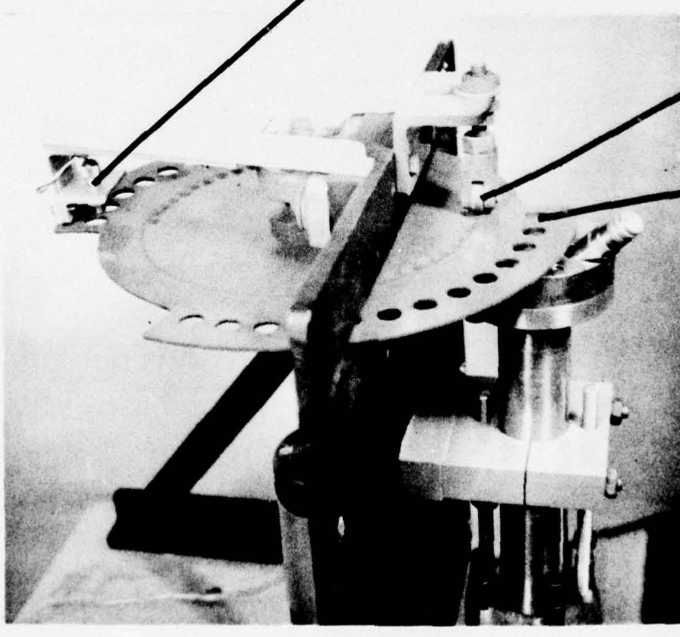


Fig. 1b Intervals of rapidly increasing pressure with superposed higher frequency oscillations are set up by a gapped wheel. (Periodic oscillations are set up by using a wheel with uniform hole spacing.)

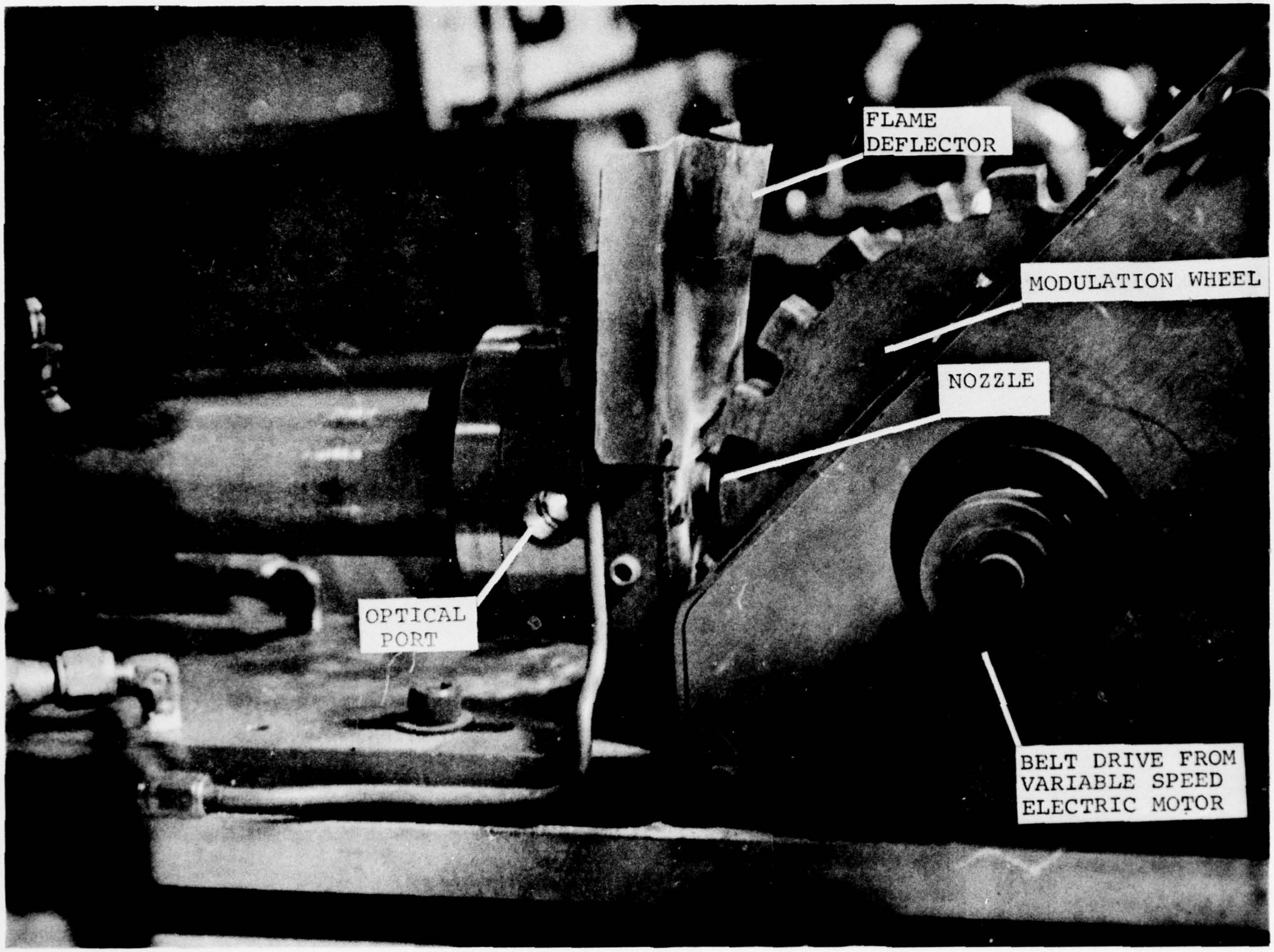


Fig. 2 Modulated throat rocket motor that uses vertical wheel.

FORCED LONGITUDINAL OSCILLATION DATA ANALYSIS

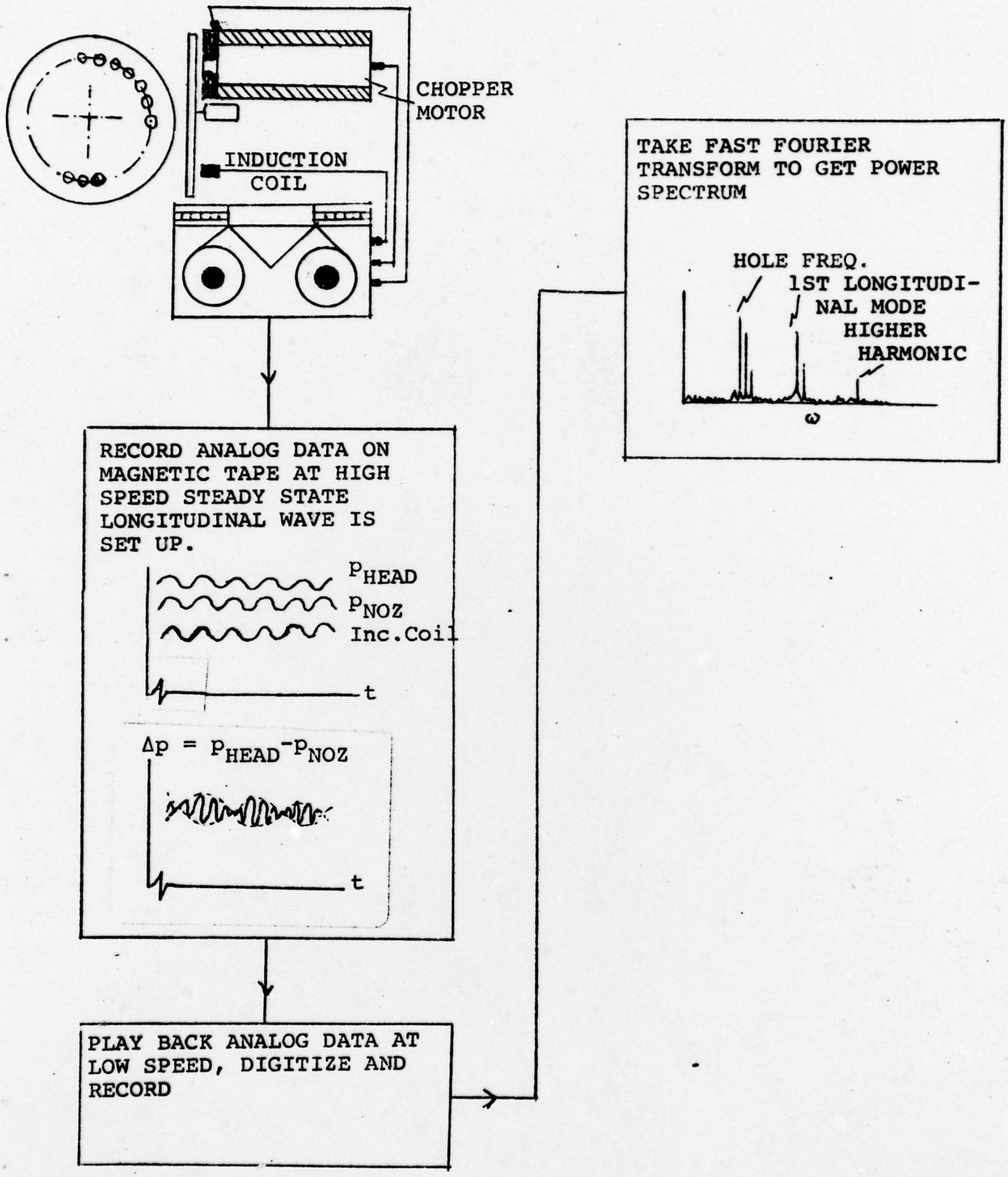


Fig. 3 A schematic representation showing modulation throat rocket motor experiment and data analysis procedures.

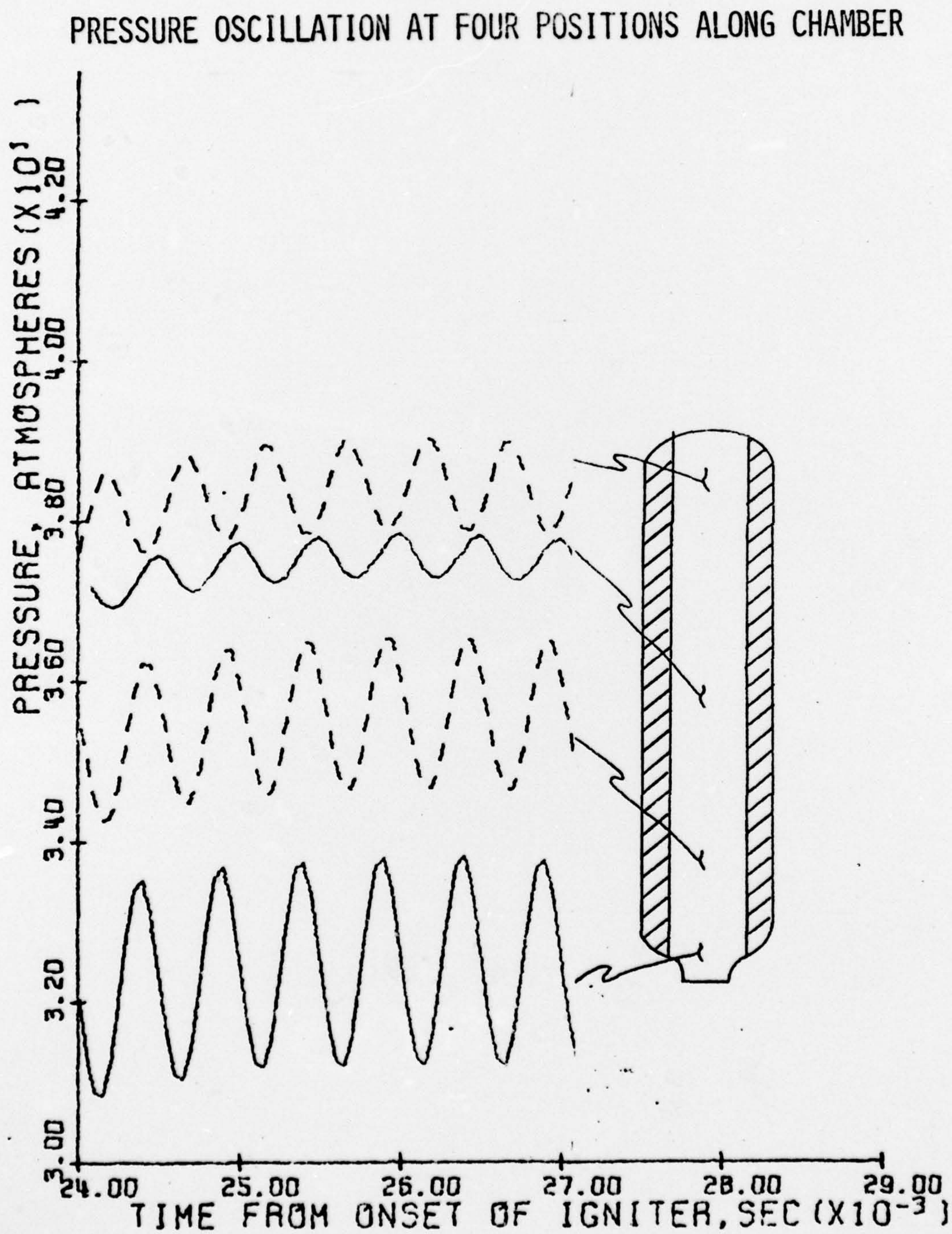


Fig. 4 Pressure transients along motor chamber showing how amplitude varies with position (modulating frequency 2000 Hz).

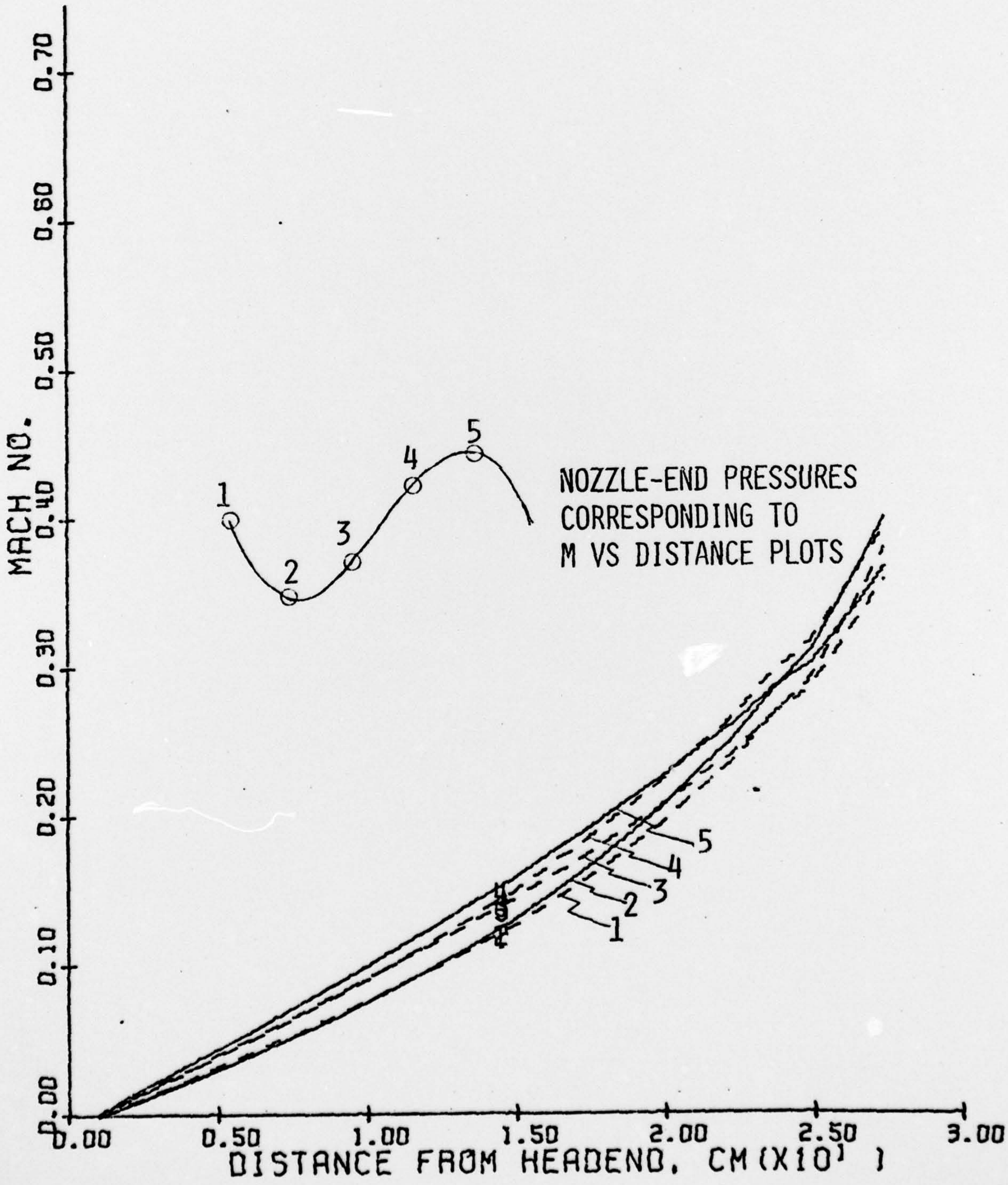
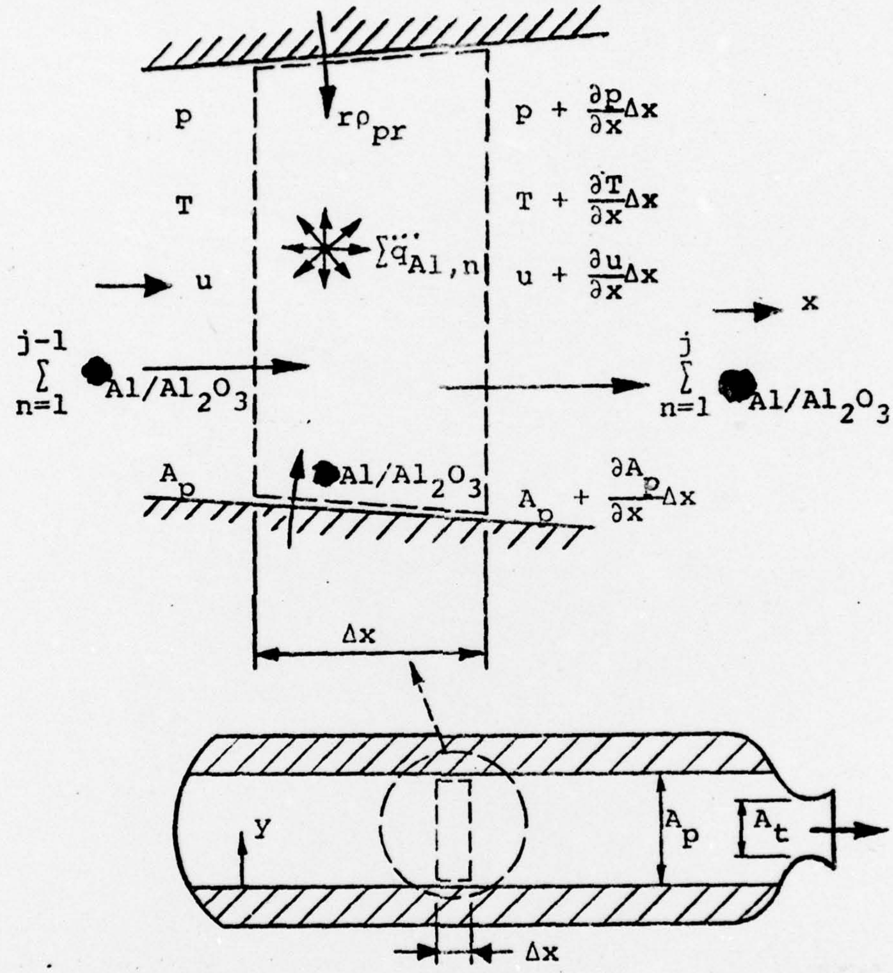


Fig. 5 Axial distribution of Mach number at five times (during one-half a period) showing that amplitude is large over most of the chamber (modulating frequency 2000 Hz).

ANALYTICAL CONTROL VOLUME OF Al/Al_2O_3
REACTING DURING THE AXIAL FLOW PROCESSES



- WELL STIRRED IN y DIRECTION.

- HEAT RELEASE FROM METAL COMBUSTION DEPENDS ON CHAMBER AND PROPELLANT PARAMETERS, $q(p, u, \bar{d}_{AP}, \ldots)$.

Fig. 6 Physical situation considered in the modeling of aluminum/alumina agglomerates burning in a rocket motor flow field.

PARTICLE GROUP MODEL FOR Al/Al_2O_3 AGGLOMERATES BURNING IN A ONE-DIMENSIONAL FLOW FIELD. THE SHADED AREAS REPRESENT THE AGGLOMERATE PATHS AND THE PERCENT OF UNREACTED AGGLOMERATES.

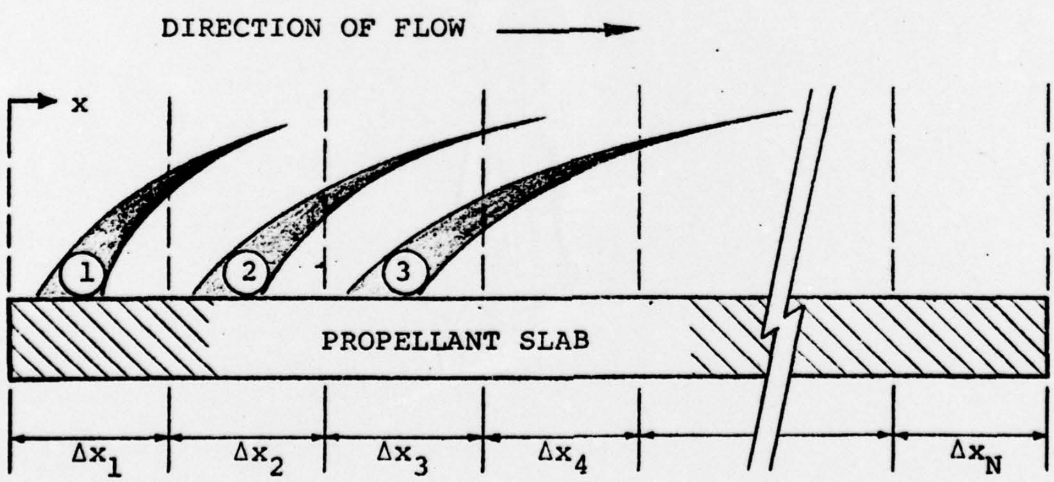


Fig. 7 Illustration of axial distribution of agglomerates with respect to their point of origin, velocity, and fraction of reaction.

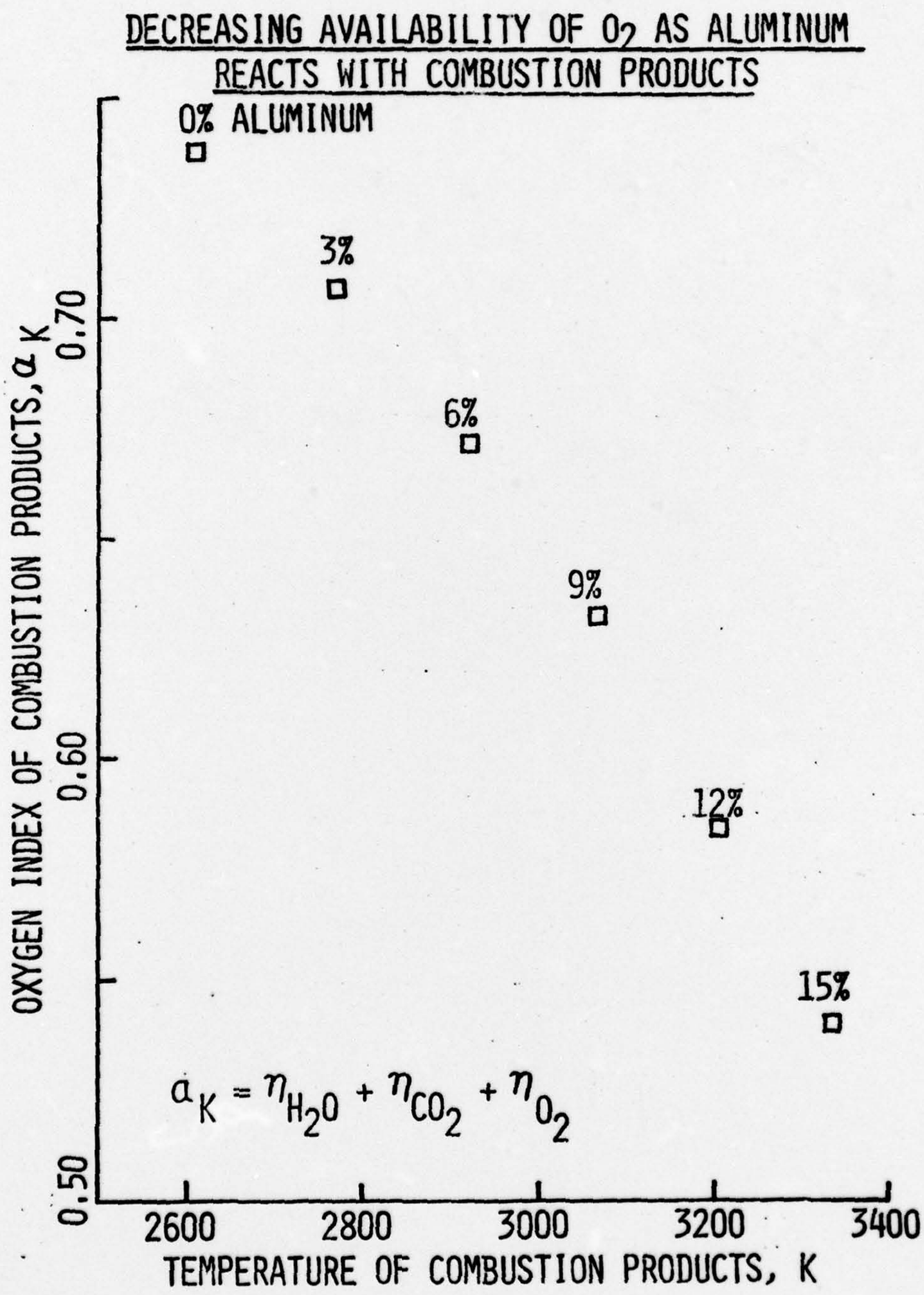


Fig. 8 Calculated increases in flame temperature and oxygen index as more aluminum is reacted.

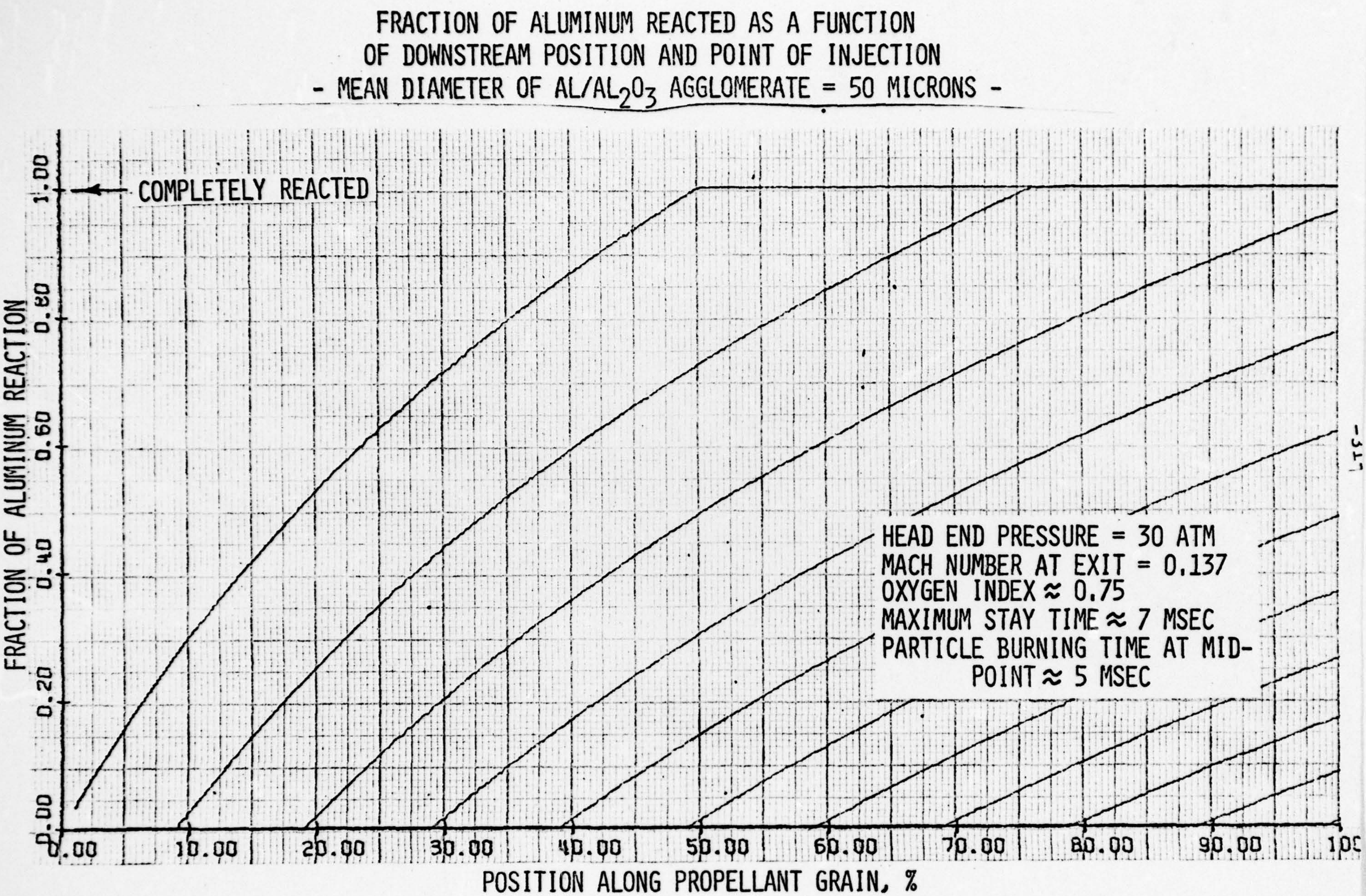


Fig. 9 Fraction of aluminum reacted as a function of downstream portion (for 50μ agglomerate).

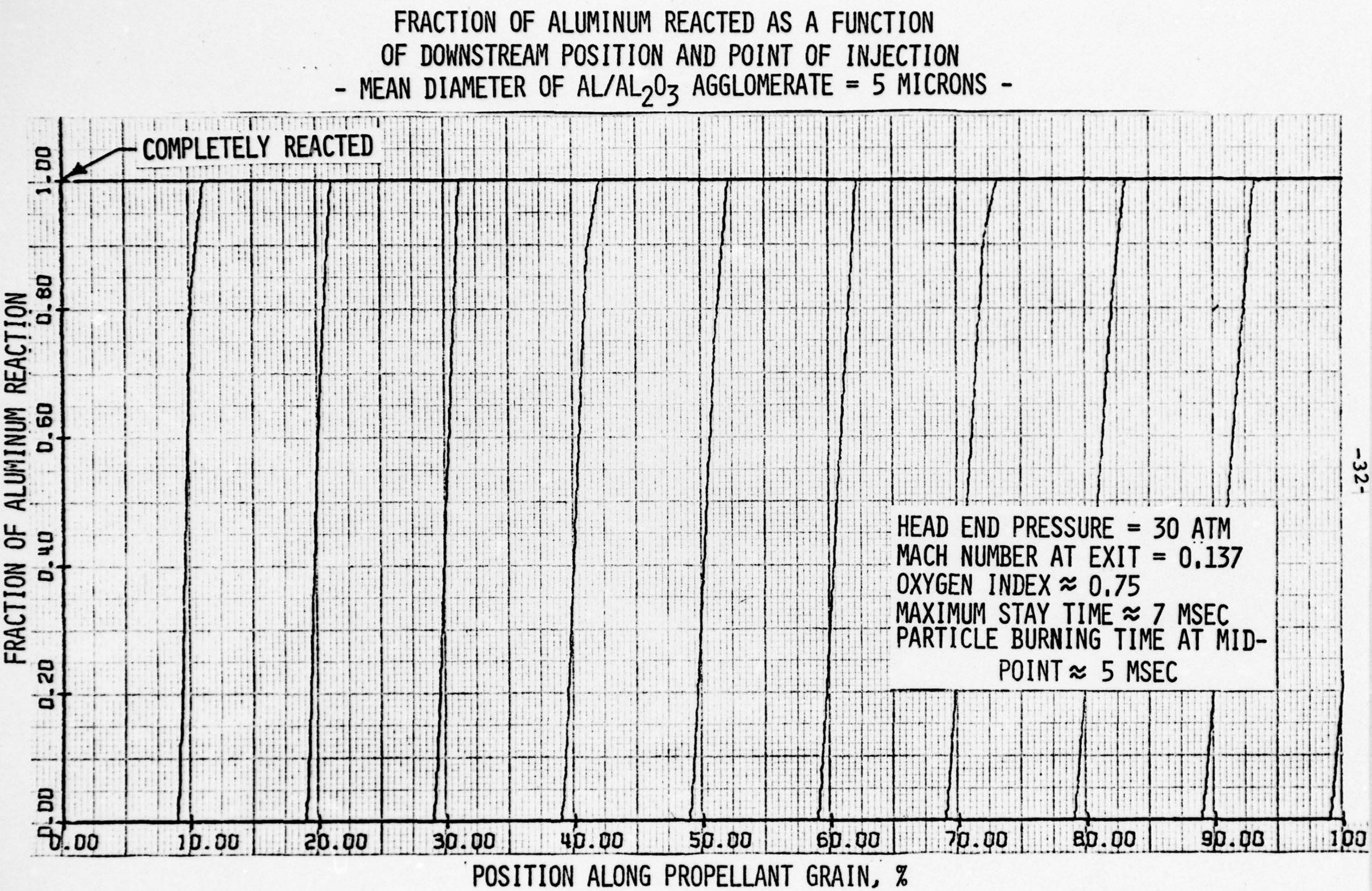
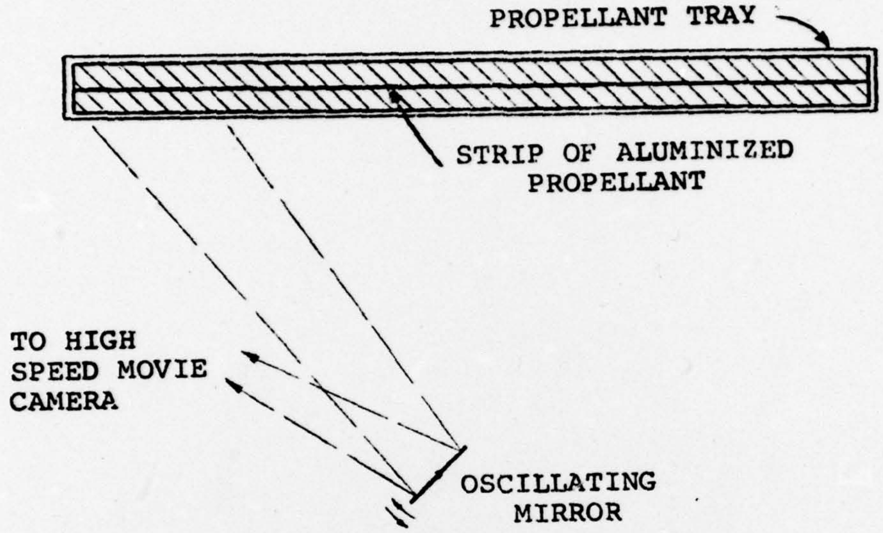


Fig. 10 Fraction of aluminum reacted as a function of downstream position (for 5μ agglomerate).

ADDITIONAL DETAILS ON PHOTOGRAPHING METAL/METAL OXIDE AGGLOMERATES BURNING IN A FLOW FIELD



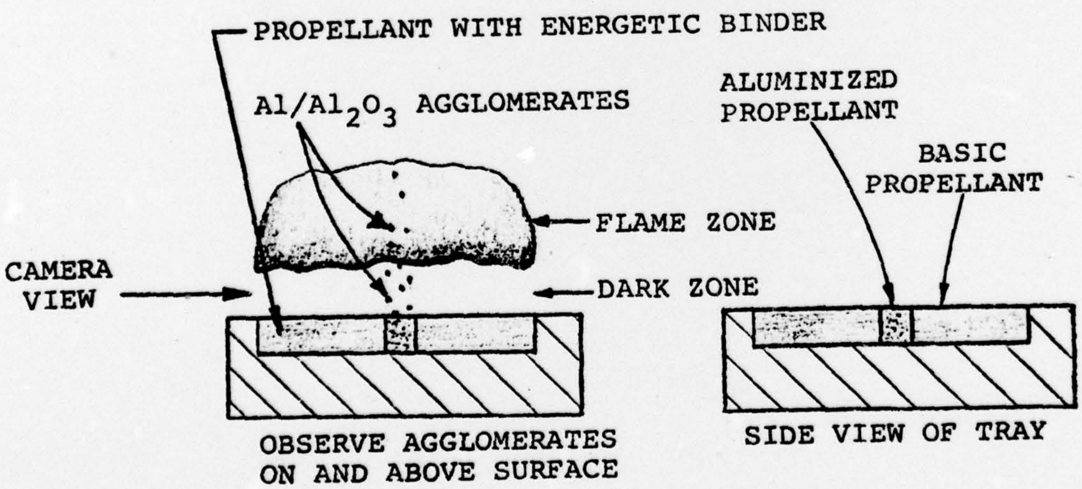


Fig. 11 A thin strip of aluminized propellant is placed between two thicker strips of nonaluminized propellants so that the camera can be focused sharply on a thin zone containing relatively few agglomerates.

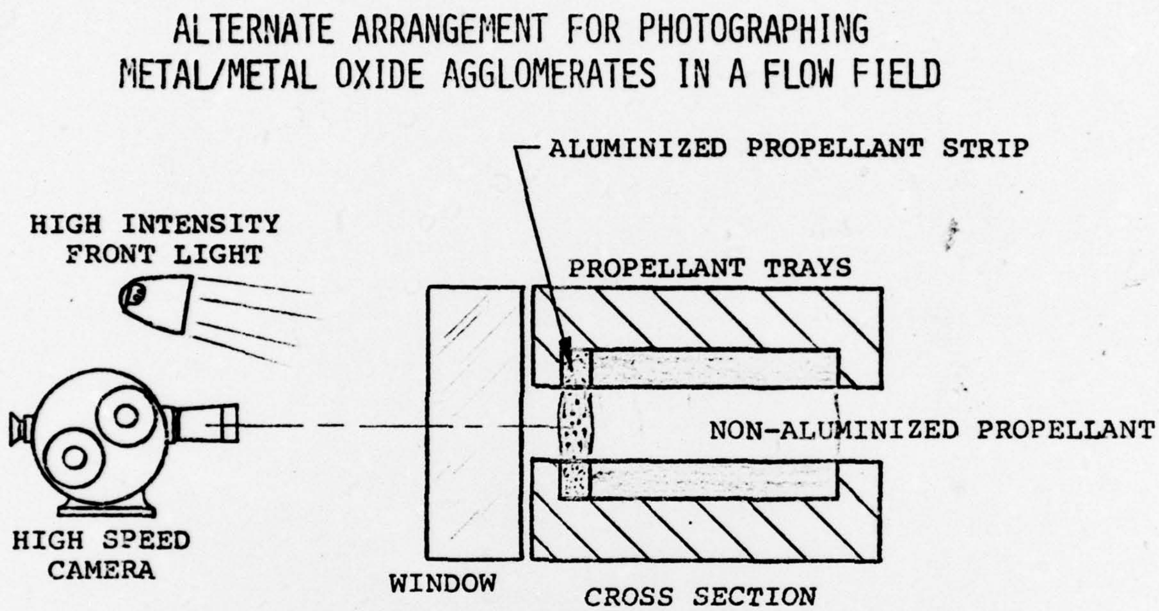


Fig. 12 An alternate arrangement for concentrating the aluminum burning in a narrow range.

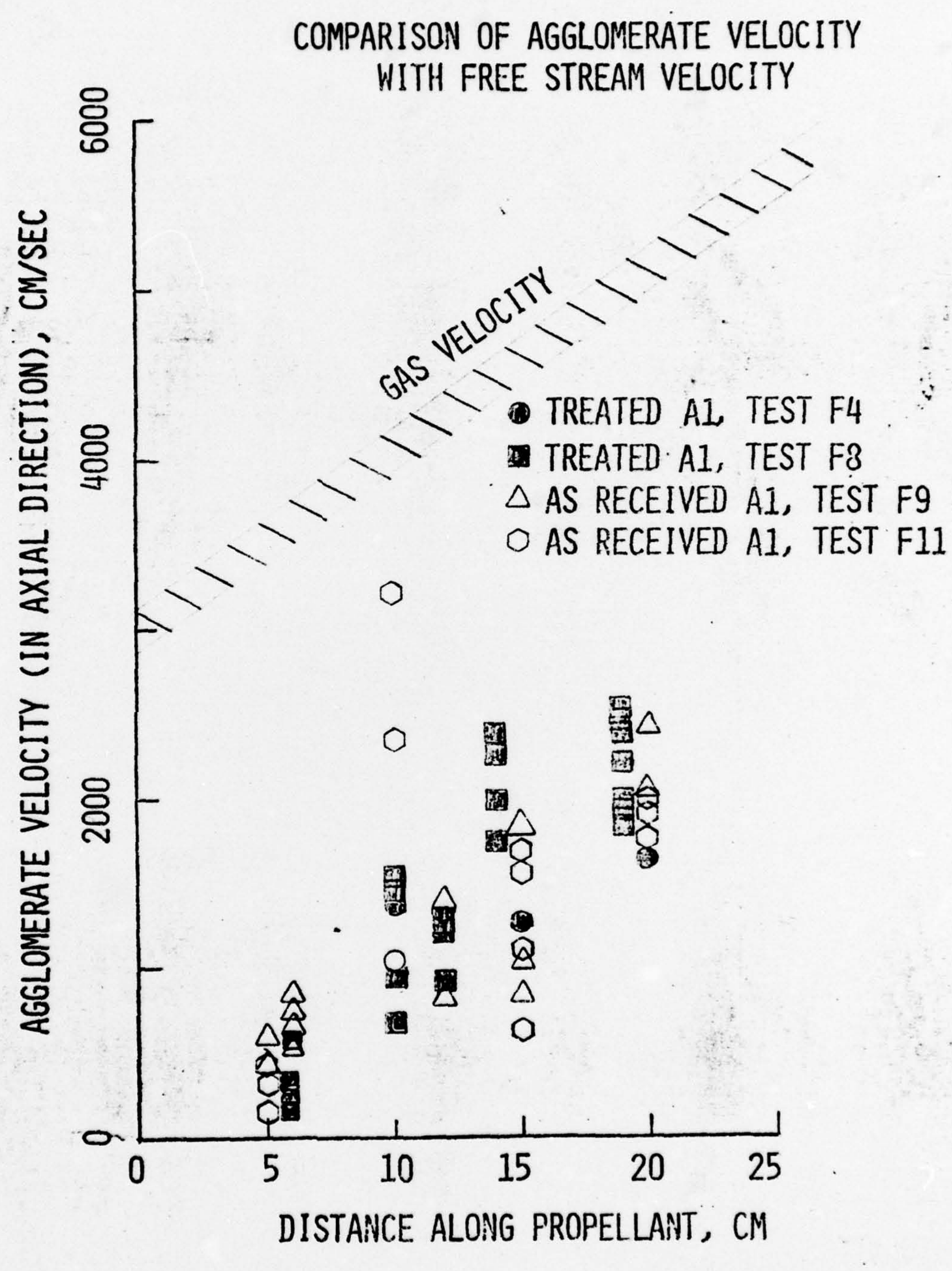


Fig. 13 Comparison of agglomerate velocities for two types of aluminum showing that the two phase flow lags are approximately the same and, thus, the agglomerate sizes are about the same.

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UNSTEADY COMBUSTION
ALUMINUM COMBUSTION
COMBUSTION INSTABILITY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The research carried out under the grant was aimed at furthering the scientific understanding of nonsteady propellant combustion behavior in rocket motor chambers. Controlled nonsteady flow and burning conditions were produced in laboratory-scale solid rocket motors by developing a device that modulated the throat area of the primary nozzle. Modulation frequencies up to 2400 Hz were obtained. The modulated throat rocket motor is being used to acquire data using AP composite propellant grains. Cold flow tests were used to study the acoustic modes and nozzle discharge characteristics. Computerized techniques were → over

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developed for conducting spectral analyses of head-end and nozzle-end pressure data. In addition, the equations describing the nonsteady one-dimensional gas dynamics and propellant combustion were formulated, and a comprehensive numerical solution was developed. The present solution takes into account the couplings among the oscillating nozzle flow, the nonsteady chamber flow, and erosive burning. Since pressure and velocity oscillations can be made to occur and decay in high loading density rocket motors with realistic grain configurations, the experiment is expected to produce propellant/chamber response functions that are relatively easy to interpret, compared to the difficult to interpret T-burner response functions. In another aspect of the study, techniques were developed for obtaining high-speed movies of aluminized double-base propellants burning in a 50 cm long window motor. In the velocity and pressure range examined (up to 60 meters/sec and 30 atmosphers), the Al/Al_2O_3 agglomerate size is in the range of 300 to 600 μ m. The photographs illustrate how cross flow affects the agglomeration on the surface and lift-off from the propellant surface.